Water Management Consumptive Use and Nitrogen Fertilization of Irrigated Winter Wheat in Western Kansas

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CONTENTS

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Water Management, Consumptive Use, and Nitrogen Fertilization of Irrigated Winter Wheat in Western Kansas

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Extensive irrigation development occurred in western Kansas and the Southern High Plains during the drought years of the 1950's. Hard red winter wheat is the major crop in this area. Considerable acreages of winter wheat are being irrigated to eliminate erratic production and prevent recurrent crop failures. The water available for irrigation from underground storage is definitely limited; therefore, its efficient use and conservation are of utmost importance. Limited knowledge and experience by irrigation farmers have led to excessive irrigation and inefficient use of water. The results of research conducted at the Garden City Branch Experiment Station, Garden City, Kans., from 1954 to 1959, show that improved irrigation water management and nitrogen fertilization can increase the efficiency of water use, maintain high yields, minimize lodging, and improve baking quality of irrigated winter wheat.

Jensen and Sletten have reported some effects of irrigation water management and nitrogen fertilization on efficiency of water use in the Southern High Plains (*9*).[2] They, as well as others, have reported the response of wheat to nitrogen fertilization and the necessity of adequate soil moisture for maximum response (*8, 10, 14, 15, 16, 17, 18*). Some investigators (*4, 5, 12*) have reported the effects of depth of soil moisture at planting and seasonal precipitation on dryland wheat yields.

Several investigators have shown the relation of grain protein content and quality to nitrogen fertilization (*3, 7, 11, 19, 20*). Very little information is available, however, on the relation of soil moisture and its interaction with nitrogen on grain quality. Comparison of dryland and irrigated wheat indicates that irrigation lowers quality.

OBJECTIVES

The overall objective was to determine management effects on efficient use of irrigation water and applied nitrogen for production of hard red winter wheat. Specific objectives included—

1. Determination of water and nitrogen management for optimum yields and efficient use of water resources.

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[1] Kansas Agricultural Experiment Station Contribution No. 47. Acknowledgment is made to Karl F. Finney, chemist, Crops Research Division, Agricultural Research Service, for performing milling and baking quality analysis of flour from the winter wheat.

[2] Italic numbers in parentheses refer to Literature Cited, p. 36.

2. Determination of effects of water and nitrogen management on plant development, yield, grain quality, and plant lodging.

3. Determination of seasonal rate of water use, total seasonal use, irrigation water requirements, and coefficients for Blaney-Criddle consumptive-use formula.

CLIMATIC AND SOIL CONDITIONS

Western Kansas weather varies considerably within seasons and from year to year. Average annual precipitation at the Garden City Experiment Station is 17.98 inches. Precipitation in individual years has ranged from 5.68 inches in the drought year of 1956 to 36.19 inches in 1923. A summary of monthly weather data during the experimental crop years, 1954, 1955, and 1957 through 1959, is presented in table 1. The annual precipitation is favorably distributed during the spring and summer crop growing season.

TABLE 1.—*Summary of monthly weather data during experimental crop years, 1954–55 and 1957–59, and long-term averages, Garden City, Kans.*[1]

Crop year and month	Average temperatures			Average wind velocity	Precipitation	Evaporation, BPI pan
	Maximum	Minimum	Mean			
1954:	° *F.*	° *F.*	° *F.*	*M.p.h.*	*Inches*	*Inches*
Oct	73	44	58	7. 6	2. 08	
Nov	54	30	42	6. 8	1. 72	
Dec	43	19	31	6 6	. 98	
Jan	42	16	29	6. 3	. 22	
Feb	60	27	44	7. 4	. 39	
Mar	54	25	39	9. 4	. 35	
Apr	73	42	57	10. 6	. 57	7. 76
May	70	49	59	10. 1	. 97	6. 74
June	92	62	77	13. 1	. 89	13. 56
Average	62	35	48	8. 7		
Total					8. 17	28. 06
1955:						
Oct	69	42	55	7. 6	1. 0	
Nov	62	29	45	6. 7	. 0	
Dec	51	18	34	5. 3	. 1	
Jan	45	17	31	4. 9	. 3	
Feb	43	14	28	8. 3	. 2	
Mar	56	24	40	8. 2	. 8	
Apr	70	43	56	9. 7	2. 6	6. 65
May	75	52	64	8. 3	4. 3	7. 12
June	81	58	69	4. 9	2. 5	7. 72
Average	61	33	47	7. 1		
Total					11. 8	21. 49

TABLE 1.—*Summary of monthly weather data during experimental crop years, 1954–55 and 1957–59, and long-term averages, Garden City, Kans.*[1]—Continued

Crop year and month	Average temperatures			Average wind velocity	Precip-itation	Evapo-ration, BPI pan
	Maxi-mum	Mini-mum	Mean			
1957:	° F.	° F.	° F.	M.p.h.	Inches	Inches
Oct	76	44	60	8. 1	0. 00	
Nov	55	24	40	5. 9	0	
Dec	51	17	34	5. 2	0	
Jan	36	10	23	6. 3	0	
Feb	54	23	38	6. 4	0	
Mar	50	29	40	7. 5	4. 32	
Apr	60	39	50	8. 8	. 24	4. 15
May	70	49	59	7. 3	3. 81	5. 38
June	84	58	71	6. 7	4. 32	7. 96
Average	60	33	46	6. 9		
Total					12. 69	17. 49
1958:						
Oct	64	45	54	7. 6	1. 16	
Nov	49	28	38	5. 6	. 63	
Dec	54	22	38	5. 2	. 00	
Jan	46	18	32	5. 1	. 89	
Feb	42	22	32	7. 5	. 25	
Mar	36	23	30	6. 5	2. 88	
Apr	60	38	49	7. 1	1. 25	3. 88
May	77	54	66	6. 1	6. 43	6. 61
June	86	59	73	6. 2	3. 27	7. 94
Average	57	34	46	6. 3		
Total					16. 76	18. 43
1959:						
Oct	73	40	56	9. 6	. 18	
Nov	55	24	39	11. 6	. 96	
Dec	46	19	32	13. 3	. 07	
Jan	39	12	26	5. 4	. 71	
Feb	44	20	32	6. 7	. 16	
Mar	55	26	40	8. 1	1. 14	
Apr	66	37	52	7. 0	. 51	5. 33
May	76	52	64	7. 5	3. 29	6. 72
June	91	61	76	7. 0	2. 82	9. 69
Average	61	32	46	8. 5		
Total					9. 83	21. 74
Long-term averages: [1]						
Oct	71	41	56	7. 1	1. 26	
Nov	55	26	40	6. 8	. 66	
Dec	45	18	32	6. 4	. 43	
Jan	43	15	29	6. 9	. 34	
Feb	48	20	34	7. 9	. 60	
Mar	55	27	41	9. 7	. 88	
Apr	66	39	52	10. 2	1. 80	6. 43
May	75	50	62	9. 5	2. 79	8. 01
June	87	60	74	9. 2	2. 96	9. 96
Average	61	33	47	8. 2		
Total					11. 72	24. 40

[1] Wind, 42 years; temperatures, 44 years; precipitation and evaporation, 51 years.

Even though spring growth of wheat occurs during the favorable rainfall period, the amount received is seldom adequate to meet the evapotranspiration demand. Some years were extremely dry during the experimental period, as in 1954. Hot, dry winds occurred during fruiting in 1954 and 1959 and were particularly severe in 1954. Temperatures for short periods may exceed 100° F. and be accompanied by wind velocities of 15 to 25 m.p.h. and low relative humidities of 10 to 20 percent.

The experiments were conducted on Richfield clay loam (tentative), a typical upland soil of the area. The surface soil is about average fertility and grades into a deep uniform loess at about 2 feet. The average water intake rate is 0.3 to 0.5 inch per hour. The moisture percentage (by weight) at field capacity is approximately 25 percent. The wilting percentage in the surface soil and in the loess subsoil is 13 and 11.5 percent, respectively. Bulk density decreases from 1.3 to 1.2 with depth. The available water-holding capacity is about 2.0 inches per foot of depth.

METHODS

This study was initiated in the fall of 1953. The experimental site was plowed out of alfalfa in 1949, planted to sugar beets in 1950, field beans in 1951, grain sorghum in 1952, and summer-fallowed in 1953. The first experimental crop year was 1954. The first 2 years of the experiment was followed by summer fallow in 1956. The experiment was revised to include detailed consumptive-use studies in 1957 and continued for a 3-year period on the same experimental site.

The experimental area was moldboard-plowed, harrowed, and floated in August in preparation for preplanting irrigation. After irrigation and germination of volunteer plants, the area was undercut with sweeps, then harrowed, fertilized, and seeded in late September.

Comanche wheat was seeded in 1954 and 1955 and Bison in 1957, 1958, and 1959 at the rate of 60 to 90 pounds per acre with a 7-inch, 13-hole disk drill. Statistical design was randomized block, split plot with 4 or 5 replicates. Irrigation basins (main plots) were 50 by 50 feet; each basin included 3 nitrogen subplots and a check plot in crop years 1954 and 1955, and 4 nitrogen subplots and a check plot in 1957 to 1959.

Water was applied to basins through gated pipe. Size of applications was determined from soil sampling before irrigation. Applications were estimated by measuring the depth of water on the plots in 1954 and 1955, and were measured accurately with a water-flow meter in 1957, 1958, and 1959.

Soil moisture samples were taken by King tube[3] at 1-foot increments to a depth of 6 feet. Percentage of moisture by weight was determined by oven drying at 105° C. Extensive samplings to determine available soil moisture and consumptive water use were taken from 1957

[3] The use of patented equipment does not imply approval of the product to the exclusion of others.

to 1959. Samples were taken periodically from emergence to harvest on all moisture-treatment plots as time and weather conditions permitted. In 1959 complete soil moisture samples for consumptive use were taken on all combinations of six moisture treatments and five nitrogen treatments. The procedure used was to sample one core per plot on all replicates for each sampling date.

Samples of wheat for yield data were cut with a Jari mower and threshed with a nursery thresher. Yields in 1958 were taken from combine-harvested samples. Straw yields were determined from plot bundle and grain weights in 1957 and 1959. Plots were harvested at the end of June or early July.

The number of irrigation treatments ranged from five to ten in different years. Some irrigation treatments were scheduled for water applications at selected stages of plant development. Deficit soil moisture treatments were included to induce plant moisture stress at selected stages. Two treatments in the first 3 years were scheduled for irrigation on the basis of available soil moisture. Three treatments in 1958 were scheduled for irrigation on the basis of soil moisture tension. Five treatments were repeated for two depths of wetting in 1954, 1955, and 1957.

Since differences between irrigation treatments receiving spring irrigations usually were not statistically significant, the effects of soil moisture management are presented by selecting three treatments. These treatments shall be referred to as "Dry," "Med" (medium), and "Wet."

The "dry" treatment consisted of fall irrigation to 6 feet (11.7 inches of available water). Preplanting irrigations were applied in the fall of 1953, 1954, 1956, and 1957. Irrigation after seeding for emergence was applied in the fall of 1958. Small applications after emergence were applied in the fall of 1954 and 1956 to improve stands.

The "med" treatment consisted of fall irrigation plus irrigation at boot stage of growth. Irrigations at boot stage wet the soil to an average depth of 4 feet. Size of application ranged from 3.5 inches in 1958 (wet spring) to 7.4 inches in 1955 (dry spring). Date of spring application varied from May 10 in 1955 to May 20 in 1958.

The "wet" treatment included fall irrigation plus three or four additional irrigations to wet the soil to an average depth of 4 feet. The stage of development when irrigated, dates of applications, and amounts of water applied for additional irrigations are shown in table 2.

Nitrogen application treatments in 1954 were check, 50, 100, and 200 pounds of N per acre. Residual effects of nitrogen applications were studied in 1955. Treatments were check, 30, 60, 90, and 120 pounds per acre applied in 1957 and 1959, with residual effects of applied N measured in 1958. Nitrogen was applied before seeding on all treatments.

TABLE 2.—*Schedule for the "wet" irrigation treatment, including stage of plant development, dates of irrigations, and amounts of water applied. In addition to the irrigations listed, a fall irrigation in all years wet the soil to 6-foot depth* [1]

Crop year	Irrigation when plant is—					Total winter and spring irrigation
	Winter dormant Dec.–Mar.	Jointing, Apr. 27–28	In boot stage, May 13–20	Flowering, May 27–28	In milk or dough stage, June 6–16	
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
1954	6. 6	5. 8	----------	5. 9	6. 0	24. 3
1955	4. 8	4. 2	3. 8	----------	4. 5	17. 3
1957	5. 4	----------	4. 8	----------	5. 1	15. 3
1958	----------	----------	3. 5	3. 5	3. 5	10. 5
1959	----------	4. 0	3. 5	3. 5	3. 5	14. 5

[1] The table does not include the fall irrigation which established uniform soil moisture at beginning of fall growth on all plots of the experiment. The amount of water applied at the fall irrigation was highly variable with plot and depended on the antecedent soil moisture of each plot; therefore, the fall irrigation is not included in the table.

RESULTS AND DISCUSSION

Consumptive Use of Water

Daily Rate of Water Use

The average daily rate of water use is reported for phenological periods beginning with fall growth in October and continuing through maturity in late June (table 3). Data are from optimum irrigation treatments where soil moisture did not limit plant development. The daily rate of use decreased from 0.07 inch per day during fall growth to 0.03 inch per day during winter dormancy. The rate of use increased consistently from 0.09 inch per day during early-spring growth to a maximum of 0.35 inch per day during flowering-to-milk stage of grain. The rate of use declined past the milk stage as the grain ripened.

The daily rate of water use is closely related to weather conditions, which can vary considerably. For example, cloudy weather with low temperatures, low wind velocities, low radiation, and high humidities reduce the rate of water use. Conversely, high temperatures, high wind velocities, high radiation, and low humidities increase water use. When averaged or accumulated over phenological periods, however, water use has been consistent. The variability during 1957 through 1959 is indicated by the point deviations from the cumulative-use curve (fig. 1).

The water-use rate decreased from a maximum during fruiting to almost zero at complete maturity. This decrease occurred while temperatures and length of day continued to increase. This effect is associated with maturation past fruiting that causes decreased transpiration and is independent of temperature and length of day.

TABLE 3.—*Average daily rate of water use by phenological periods for irrigated winter wheat grown under optimum soil moisture, Garden City, Kans., 1957–59*

Period	Water use
	Inch per day
Fall (October)	0.07
Winter (November–February)	.03
Beginning of spring growth to the jointing stage (March–April)	.09
Jointing-to-boot stage (May 1–15)	.16
Boot-to-flower stage (May 15–28)	.25
Flower-to-milk stage of grain (May 28–June 6)	.35
Milk-to-dough stage of grain (June 6–13)	.30
Dough stage to maturity (June 13–28)	.15

Cumulative Use of Water

Seasonal cumulative use of water by wheat grown under soil moisture for near maximum yields is illustrated in figure 1. Four to five inches of water were used from fall emergence through winter dormancy in early March. Moderate use during spring growth increased the total use to about 11.5 to 12.5 inches at boot stage. A period of rapid water use followed that continued through grain development. The crop used 20 to 21 inches of water to the soft dough stage. The total seasonal use averaged 23 to 24 inches.

Irrigation Water Requirements

The irrigation water requirements depend primarily upon four factors: (1) Available soil moisture at beginning of season, (2) amount and distribution of seasonal precipitation, (3) consumptive use of water by the crop, and (4) irrigation efficiency. The seasonal water use can be predicted rather accurately. The stored soil moisture in the root profile can be measured or estimated from soil sampling. The efficiency of irrigation, defined as the percentage of water pumped or delivered to the farm that is stored in the soil for plant use, can be estimated for any given system of design and management. The remaining factor, which is unpredictable in western Kansas, is precipitation. In the 5 years of this experiment, the spring growing season precipitation from March 1 to June 15 ranged from 2.67 inches in 1954 to 12.12 inches in 1958. Therefore, it is desirable to estimate irrigation water requirements on an expected frequency basis.

Estimated frequency of irrigation water requirements is presented in table 4. Irrigation requirements are given when available soil moisture storage at emergence is 5, 8, and 11 inches and when seasonal precipitation is 6 to 18 inches. For 1 year in 10, seasonal precipitation (October through June) at the Garden City Experiment Station is expected to be less than 6.0 inches, and for 1 year in 10 greater than 18.0 inches. In addition to the irrigation requirements after emergence (table 4), a preplanting irrigation will be required usually to provide most of the available soil moisture indicated at emergence.

With 5 inches of available soil moisture at emergence, the irrigation water requirement to be delivered to the farm will range from 18.5 to

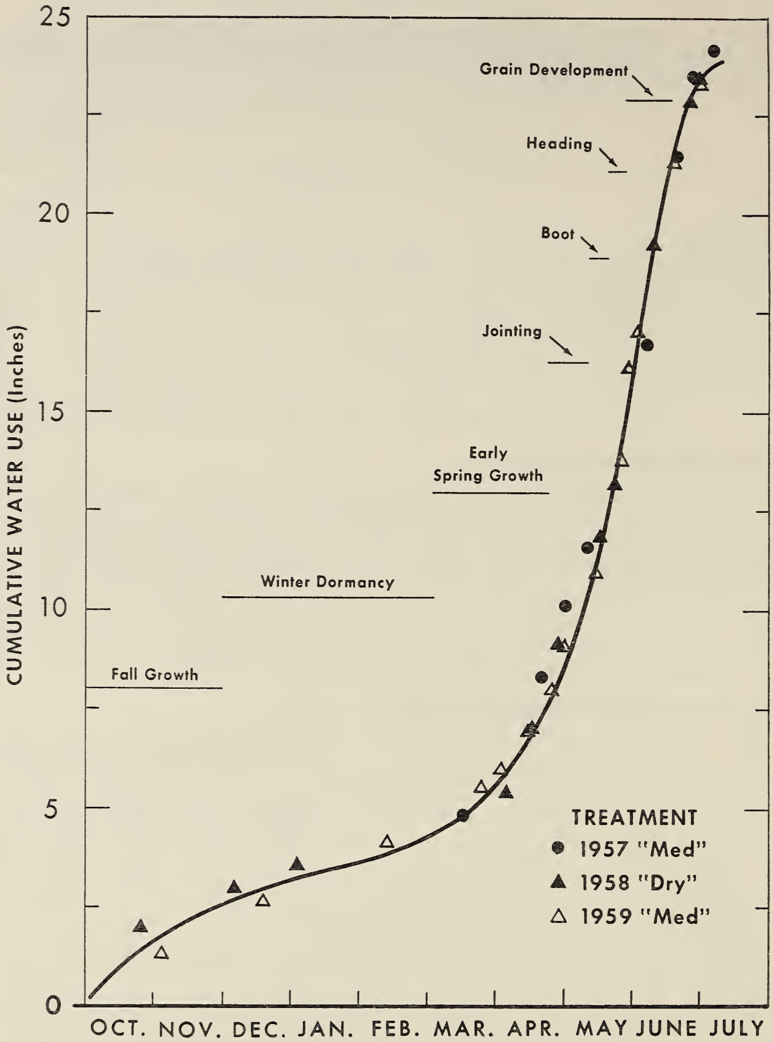

FIGURE 1.—Cumulative seasonal water use by irrigated winter wheat grown under adequate soil moisture for near maximum yields, 1957–59.

20 inches for 1 year in 10, when the seasonal precipitation is less than 6.0 inches. No irrigation water will be required 1 year in 10 when the seasonal precipitation exceeds 18.0 inches. With 8.0 inches of available soil moisture at emergence, no additional irrigation water is required 1 year in 4 when the precipitation exceeds 14.6 inches. With 11.0 inches of available soil moisture at emergence, no additional

irrigation water is required 1 year in 2. These irrigation water requirements were calculated with an average irrigation efficiency of 65 percent.

For the upland silt loam or finer textured soils of western Kansas, a preplanting irrigation to 6 feet will store about 10 to 12 inches of available soil moisture. Therefore, for most years one additional irrigation in the spring will supply the irrigation water requirement for maximum yields.

Table 4.—*Expected frequency of irrigation water requirements for selected conditions of available soil moisture (ASM) at emergence in 0- to 6-foot depth and seasonal precipitation. Data are based on water use for winter wheat grown under optimum soil moisture for plant development, Garden City, Kans., 1957–59*

ASM at emergence (inches)	Seasonal precipitation (Oct.–June)			Irrigation water	
	Amount	Expected frequency [1]		Stored in soil	Pumped or delivered to farm [2]
	Inches	*Percent*	*Years*	*Inches*	*Inches*
5. 0	<6. 0	10	1 in 10	12. 0–13. 0	18. 5–20. 0
	<8. 5	25	1 in 4	9. 5–10. 8	14. 6–16. 2
	>11. 0	50	1 in 2	7. 0– 8. 0	10. 8–12. 3
	>14. 6	25	1 in 4	3. 4– 4. 4	5. 2– 6. 8
	>18. 0	10	1 in 10	0	0
8. 0	<6. 0	10	1 in 10	9. 0–10. 0	13. 8–15. 4
	<8. 5	25	1 in 4	6. 5– 7. 5	10. 0–11. 5
	>11. 0	50	1 in 2	4. 0– 5. 0	6. 2– 7. 7
	>14. 6	25	1 in 4	0	0
	>18. 0	10	1 in 10	0	0
11. 0	<6. 0	10	1 in 10	6. 0– 7. 0	9. 2–10. 8
	<8. 5	25	1 in 4	3. 5– 4. 5	5. 4– 6. 9
	>11. 0	50	1 in 2	0	0
	>14. 6	25	1 in 4	0	0
	>18. 0	10	1 in 10	0	0

[1] Expected frequency of seasonal precipitation based on 50 years of data at the Garden City Experiment Station, Garden City, Kans.

[2] Calculated for irrigation efficiency of 65 percent and total seasonal water use of 23 to 24 inches.

Coefficients for Blaney-Criddle Consumptive-Use Formula

Consumptive-use data for 1957 through 1959 were combined to calculate monthly and the seasonal empirical coefficients for the Blaney-Criddle consumptive-use formula (table 5). This formula relates consumptive use to percentage of daytime hours of the year and the mean temperatures in an empirical relationship (*1*).

The basic consumptive-use formula is

$$u=kf, \text{ where}$$

u=Consumptive use for a given period;
k=Empirical coefficient for the consumptive-use period;
f=Consumptive-use factor for the same perod.

The relationship between the consumptive-use factor and temperature and daytime hours is

$$f=\frac{t \times p}{100}, \text{ where}$$

t=Mean temperature for the consumptive-use period in degrees Fahrenheit;
p=Percentage of daytime hours of the year for the consumptive-use period.

The equation expressed for the growing season is

$$U=KF, \text{ where}$$

U=Cumulated consumptive use for the growing season;
K=Empirical coefficient for the growing season;
F=Sum of consumptive-use factors for all periods within the the growing season.

The coefficients can be used with temperature data and percentage of daytime hours of the year to estimate consumptive use in areas similar to the experimental locations.

Monthly coefficients (k) increased from a minimum of 0.32 during winter dormancy to a maximum of 1.08 during May. The seasonal coefficient (K) was 0.71. In addition to consumptive-use coefficients, table 5 presents mean monthly temperatures, percentage of daytime hours of the year, and monthly consumptive use.

Table 5.—*Monthly coefficients (k) for the Blaney-Criddle consumptive-use formula, and totals for growing season (K), irrigated winter wheat grown under optimum soil moisture, Garden City, Kans., 1957–59* [1]

Month and growing season	Mean monthly temperature (t)	Daytime hours (p)	Consumptive-use factor $\left(f=\frac{t \times p}{100}\right)$	Monthly consumptive use (u)	Average daily use	Consumptive-use coefficient (k)
	° F.	*Percent*		*Inches*	*Inch/day*	
October (10–31)	53.6	5.28	2.83	1.62	0.077	0.57
November	38.8	6.82	2.65	.84	.028	.32
December	35.0	6.66	2.33	.76	.025	.33
January	28.8	6.87	1.98	.72	.023	.36
February	31.8	6.79	2.16	.73	.026	.34
March	36.7	8.34	3.89	1.56	.050	.40
April	49.9	8.90	4.44	3.60	.120	.81
May	63.0	9.92	6.25	6.78	.219	1.08
June	73.4	9.95	7.30	7.27	.242	1.00
Growing season (K)			33.83	23.88		.71

[1] Latitude, Garden City, Kans.=37°59′ N.

Effects of Water Management and Nitrogen Fertilization

Grain Yields

The effects of water management and nitrogen fertilization on grain yields are presented in table 6. Spring growing season precipitation, March 1 to June 15, is used as a climatic classification for individual years. Precipitation during the period ranged from 2.67 inches (dry) in 1954 to 11.78 inches (wet) in 1958. Rainfall after early-dough stage, about June 15, did not appear to affect grain yields. Irrigation treatments are compared with yields from dryland fallow.

Irrigation increased yields over dryland fallow in all years. For the 5-year period, dryland fallow yields averaged 21.0 bushels per acre as compared to 45.0 bushels per acre for the "dry" treatment, which was irrigated in the fall only. One spring irrigation at boot stage increased average yields to 48. 6 bushels per acre ("med" treatment). The comparison of dryland to irrigated yields is only indicative of response to irrigation, since dryland plots were on a separate experimental area and yields were an inadequate sampling of long-term climatic effects.

The "med" and "wet" irrigation treatments significantly increased yields over the "dry" treatment in only one year, the dry spring of 1954. Severe moisture stress on the "dry" treatment in 1954 decreased yields from 47.8 to 32.8 bushels per acre. One irrigation at boot stage largely prevented the development of moisture stress and resulted in near maximum yields. In years of approaching normal or above normal spring precipitation, the "med" and "wet" treatments did not increase yields significantly over the "dry" treatment.

The response to nitrogen fertilization is included in table 6. Since the soil was above average in fertility, this response was generally small. Applied nitrogen increased yields up to 6 bushels per acre for rates of 30 to 60 pounds per acre. Residual effects were studied in 1955 and 1958. In 1955, the 100- and 200-pound per acre rates increased yields by 5.8 and 9.5 bushels per acre, respectively. No residual effects were apparent in 1958. The yield response to applied nitrogen was significantly curvilinear. The maximum response generally occurred for the 30- to 60-pound-per-acre rates. Some leveling off or depression of yield was observed at the higher rates. The study did not provide the low range of nitrogen availability to determine its interrelationship with soil moisture.

The effects of depleting available soil moisture to limited levels at selected stages of plant development are presented in table 7. Limited available soil moisture periods were terminated by irrigations. The yield reductions were determined by comparing limited available soil moisture treatments with the "wet" control treatment. Depletion of soil moisture at boot stage to 12 percent available in 0 to 2 feet and 19 percent in 0- to 4-foot depth did not decrease yields significantly in 1955. Similar depletion at flowering stage in 1959 did not significantly affect grain yields. A significant decrease in yield did not occur until soil moisture was depleted to the wilting point in the 0- to 4-foot depth, at the milk to soft dough stage of grain, and approached the wilting point in the 6-foot profile.

TABLE 6.—*Effect of water management and applied and residual nitrogen on grain yields for different climatic years compared with dryland fallow yields, Garden City, Kans., 1954–59* [1]

Year	Precipitation Mar. 1–June 15 [2]	Dry-land fal-low [3]	Nitrogen rate	Irrigation treatments			
				"Dry"	"Med"	"Wet"	Average
	Inches	*Bu./acre*	*Lb./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*
1954	2.67 (dry)	2. 9	Check	33. 3	45. 4	47. 4	42. 0
			50	32. 7	47. 8	53. 1	44. 5
			100	33. 6	45. 2	48. 3	42. 4
			200	31. 6	44. 4	42. 4	39. 5
			Average	32. 8	45. 7	47. 8	42. 1

Irrigation mean square=2, 309. 26**
Main plot error=77. 44
Replicates=5

Nitrogen mean square=131. 04**
N×I mean square=44. 35
Subplot error=27. 61

1955	8.20 (above normal).	35. 1	Residual check [4]	42. 6	43. 9	42. 4	43 0
			50	44. 5	45. 5	42. 6	44. 2
			100	47. 6	50. 2	48. 5	48. 8
			200	49. 8	55. 8	52. 0	52. 5
			Average	46. 1	48. 8	46. 4	47. 1

Irrigation mean square=89. 36
Main plot error=123. 76
Replicates=5

Nitrogen mean square=470. 35**
N×I mean square=16. 97
Subplot error=18. 81

1957	8.90 (above normal).	8. 3	Check	49. 8	49. 5	55. 6	51. 6
			30	54. 1	55. 8	54. 2	54. 7
			60	51. 0	52. 8	53. 2	52. 3
			90	49. 1	47. 6	50. 7	49. 1
			120	51. 8	49. 8	50. 9	50. 8
			Average	51. 2	51. 1	52. 7	51. 7

Irrigation mean square=20. 76
Main plot error=22. 12
Replicates=5

Nitrogen mean square=58. 91**
N×I mean square=14. 61
Subplot error=7. 47

See footnotes at end of table.

TABLE 6.—*Effect of water management and applies and residual nitrogen on grain yields for different climatic years compared with dryland fallow yields, Garden City, Kans., 1954–59*—Continued

Year	Precipitation Mar. 1–June 15 [2]	Dry-land fal-low [3]	Nitrogen rate	Irrigation treatments			
				"Dry"	"Med"	"Wet"	Average
	Inches	*Bu./acre*	*Lb./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*
1958	11.78 (wet)	32. 6	Residual check [4]	51. 9	48. 8	50. 7	50. 5
			30	52. 9	50. 2	51. 6	51. 6
			60	54. 6	49. 7	49. 7	51. 3
			90	48. 0	49. 9	49. 5	49. 1
			120	47. 3	50. 3	49. 8	49. 1
			Average	50. 9	49. 8	50. 3	50. 3

Irrigation mean square=8. 83
Main plot error=16. 41
Replicates=5

Nitrogen mean square=20. 32
N×I mean square=17. 78
Subplot error=16. 08

1959	4.94 (below normal).	26. 2	Check	42. 0	45. 4	46. 5	44. 6
			30	45. 8	48. 4	48. 0	47. 4
			60	43. 7	48. 4	49. 2	47. 1
			90	44. 1	48. 4	49. 9	47. 5
			120	44. 9	48. 0	47. 3	46. 7
			Average	44. 1	47. 7	48. 2	46. 7

Irrigation mean square=98. 10*
Main plot error=22. 30
Replicates=4

Nitrogen mean square=16. 58*
N×I mean square=3. 05
Subplot error=7. 09

Average (all years)	21. 0	----------	45. 0	48. 6	49. 1	47. 6

[1] *=Statistically significant at 5-percent level; **=statistically significant at 1-percent level.
[2] 50-year average precipitation, March 1–June 15=6.95 inches.
[3] Yields from dryland fallow were taken from variety tests, Garden City Experiment Station. Dryland fallow yields in 1957 were limited by delayed emergence (spring).
[4] Carryover from nitrogen application the previous year.

TABLE 7.—*Effects of minimum available soil moisture depletion at selected stages of plant development on grain yield, Garden City, Kans., 1954–59*

Stage of development and year	Minimum depletion of available soil moisture at—			Yield reduction [1]
	0 to 2 feet	0 to 4 feet	0 to 6 feet	
	Percent	*Percent*	*Percent*	*Percent*
Boot:				
1954	21	19	25	4.6
1955	12	19	27	5.2
1957	29	38	45	3.1
1958	74	68	70	1.0
1959	28	33	41	1.0
Flowering:				
1958	62	64	67	−1.5
1959	18	19	28	3.8
Milk:				
1958	47	49	54	.4
1959	1	2	10	5.8
Soft dough, 1959	0	0	7	*8.2

[1] * = Statistically significant at the 5-percent level.

The ability of winter wheat to maintain development under very low soil moisture availability is related to an extensive rooting system in both density and depth. The deep uniform loess subsoil, with its relatively low bulk density of 1.26, provided favorable conditions for rooting development. Roots were observed to a depth of 6 feet in early spring. Under favorable conditions in Nebraska, winter wheat roots were measured to a depth of 13 feet and moisture extraction to 8 feet (*11*). The major root zone for moisture extraction, however, was the top 4 feet. When most of the available soil moisture in this depth was depleted, transpiration demand was largely met by moisture extraction from greater soil depth.

Wheat roots have the ability to explore thoroughly the soil for available moisture with increasing plant development and demand for water. Therefore, in a deep soil wet to field capacity, a large volume of stored soil moisture is readily available for crop use. The ability of wheat roots to extract the soil moisture below 15 atmospheres tension also indicated an extensive rooting system that thoroughly explores the soil for moisture extraction.

Straw Yields and Straw/Grain Ratios

Straw yields were determined from the 1957 and 1959 experiments. From the grain and straw yield, the straw/grain ratios (pounds of straw produced per pound of grain) were calculated. Spring irrigation increased straw yields considerably without significantly increasing grain yields. Straw yields were increased from 6,380 to 7,580 pounds per acre in 1957 and from 4,500 to 5,490 pounds per acre in 1959 (table 8).

TABLE 8.—*Effect of water management and applied nitrogen on straw yields in pounds per acre, Garden City, Kans., 1957 and 1959* [1]

Year	Nitrogen rate	Irrigation treatments			Average
		"Dry"	"Med"	"Wet"	
		Lb./acre	*Lb./acre*	*Lb./acre*	*Lb./acre*
1957	Check	6, 360	6, 300	7, 580	6, 750
	30	6, 440	7, 160	7, 800	7, 130
	60	6, 080	7, 560	7, 500	7, 050
	90	6, 420	7, 660	7, 540	7, 110
	120	6, 600	7, 180	7, 540	7, 110
	Average	6, 380	7, 170	7, 590	7, 050
Irrigation mean square=8, 904, 674** Main plot error=600, 680 Replicates=5			Nitrogen mean square=518, 797* N × I mean square 556, 490** Subplot error=142, 147		
1959	Check	4, 030	5, 320	4, 990	4, 780
	30	4, 780	5, 480	5, 580	5, 280
	60	4, 300	5, 790	5, 610	5, 230
	90	4, 500	5, 300	5, 810	5, 200
	120	4, 840	5, 480	5, 470	5, 260
	Average	4, 500	5, 470	5, 490	5, 150
Irrigation mean square=6, 512, 520** Main plot error=480, 299 Replicates=4			Nitrogen mean square=555, 677* N×I mean square=208, 080 Subplot error=168, 500		

[1] *=Statistically significant at the 5-percent level; **=statistically significant at the 1-percent level.

The response curves of applied nitrogen to increased straw yields were significantly curvilinear. Nitrogen application rate of 30 pounds per acre increased average straw yields by 380 to 500 pounds per acre. Higher rates had a leveling-off effect.

The critical growth period for rank straw development was spring tillering through boot stage. High soil moisture and nitrogen availability during this period stimulated rank growth. High straw yields involve increased problems in lodging, harvesting, and management of stubble.

A high grain yield is desired that gives a low straw/grain ratio. The most desirable straw/grain ratios occurred on the "dry" treatment which measured 2.09 pounds of straw per pound of grain in 1957 and 1.70 in 1959 (table 9). Irrigations in 1957 increased the straw/grain ratio to 2.41 on the "wet" treatment. None of the straw/grain ratios in 1959 was excessively high.

Seasonal Water Use and Efficiency of Use

The total seasonal water use for selected irrigation treatments ranged from 16.21 inches on the "dry" treatment in 1954 to 26.32

686-433—63——3

inches on the "wet" treatment in 1957. In 1959, the seasonal use ranged from 19.06 inches for the "dry" treatment to 25.40 inches for the "wet" treatment. Variability in seasonal water use was related primarily to soil moisture availability. The highest water use measured was 26.32 inches in 1957.

TABLE 9.—*Effect of water management and applied nitrogen on straw/grain ratios, pounds of straw per pound of grain, Garden City, Kans., 1957 and 1959* [1]

Year	Nitrogen rate	Irrigation treatments			Average
		"Dry"	"Med"	"Wet"	
	Lb./acre	*Lb./lb.*	*Lb./lb.*	*Lb./lb.*	*Lb./lb.*
1957	Check	2. 18	2. 12	2. 27	2. 19
	30	1. 99	2. 14	2. 40	2. 18
	60	1. 99	2. 43	2. 40	2. 37
	90	2. 18	2. 69	2. 49	2. 45
	120	2. 12	2. 40	2. 48	2. 33
	Average	2. 09	2. 36	2. 41	2. 28

Irrigation mean square=2. 8587**
Main plot error=0. 1824
Replicates=5
Nitrogen mean square=0. 7754**
N×I mean square=0. 3382**
Subplot error=0. 9951

Year	Nitrogen rate	"Dry"	"Med"	"Wet"	Average
1959	Check	1. 59	1. 77	1. 79	1. 72
	30	1. 74	1. 80	1. 96	1. 83
	60	1. 64	1. 84	1. 88	1. 79
	90	1. 72	1. 81	1. 98	1. 84
	120	1. 80	1. 78	1. 92	1. 83
	Average	1. 70	1. 80	1. 91	1. 80

Irrigation mean square=0. 2123
Main plot error=0. 0498
Replicates=4
Nitrogen mean square=0. 0315
N×I mean square=0. 0169
Subplot error=0. 0142

[1] **=Statistically significant at the 1-percent level.

Grain yields were plotted against seasonal water use in figure 2. The relation between yield and seasonal water use appeared to be linear for low water use, but tapered off past 20 to 22 inches. Seasonal water use for near maximum yields was 22 to 24 inches. Data are insufficient to define adequately the seasonal water use-yield relations below 20 inches of water use.

The efficiency of water use for grain production was measured in bushels of grain produced per acre-inch of water used. The "dry" treatment produced grain most efficiently for the period 1957–59. Within this 3-year period, the "dry" treatment incurred only slight moisture stress. The maximum efficiency measured was 2.39 bushels per acre-inch in 1959 (table 10).

The relation between the total seasonal water use and efficiency of use is presented in figure 3. This curve includes three moisture treat-

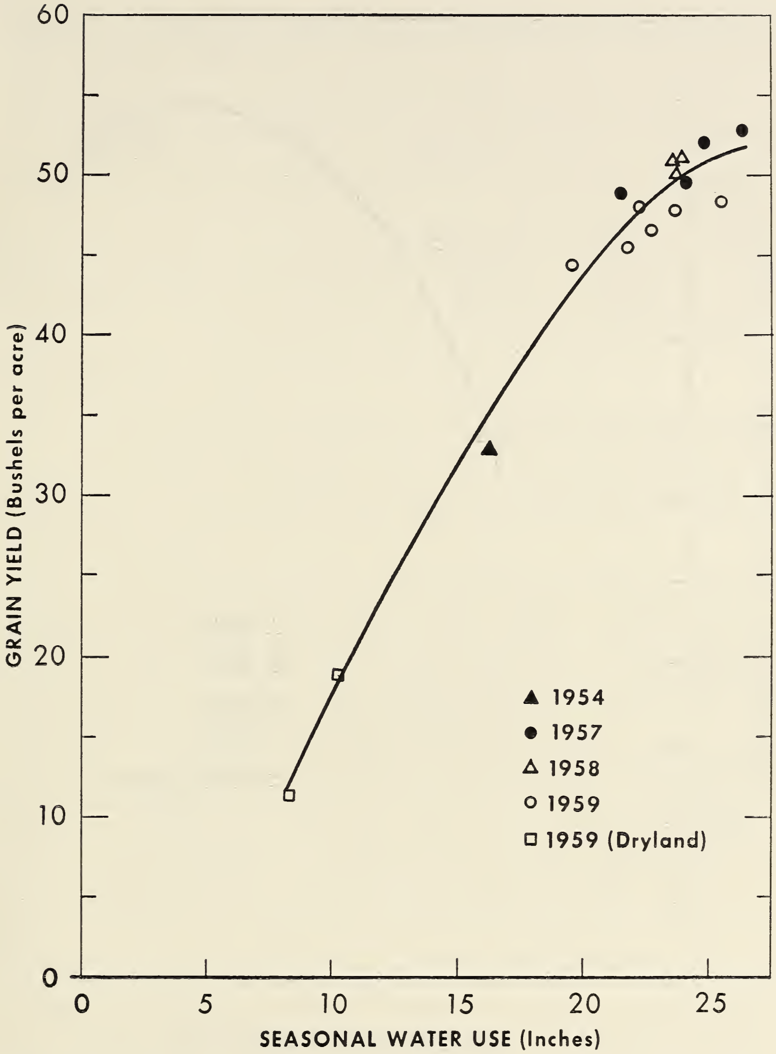

FIGURE 2.—Relation between seasonal water use and grain yields, 1954 and 1957 to 1959.

ments that incurred severe stress. The efficiency of water use under severe stress conditions decreased considerably. Maximum efficiency of use occurred for seasonal water use of 18 to 22 inches. These data indicate the maximum efficiency of water use to be about 2.4 bushels per acre-inch under these conditions.

The curve in figure 3 also illustrates the decrease in efficiency of water use when higher soil moisture was maintained. This decrease was consistent between seasonal water use of 22 to 26 inches. The

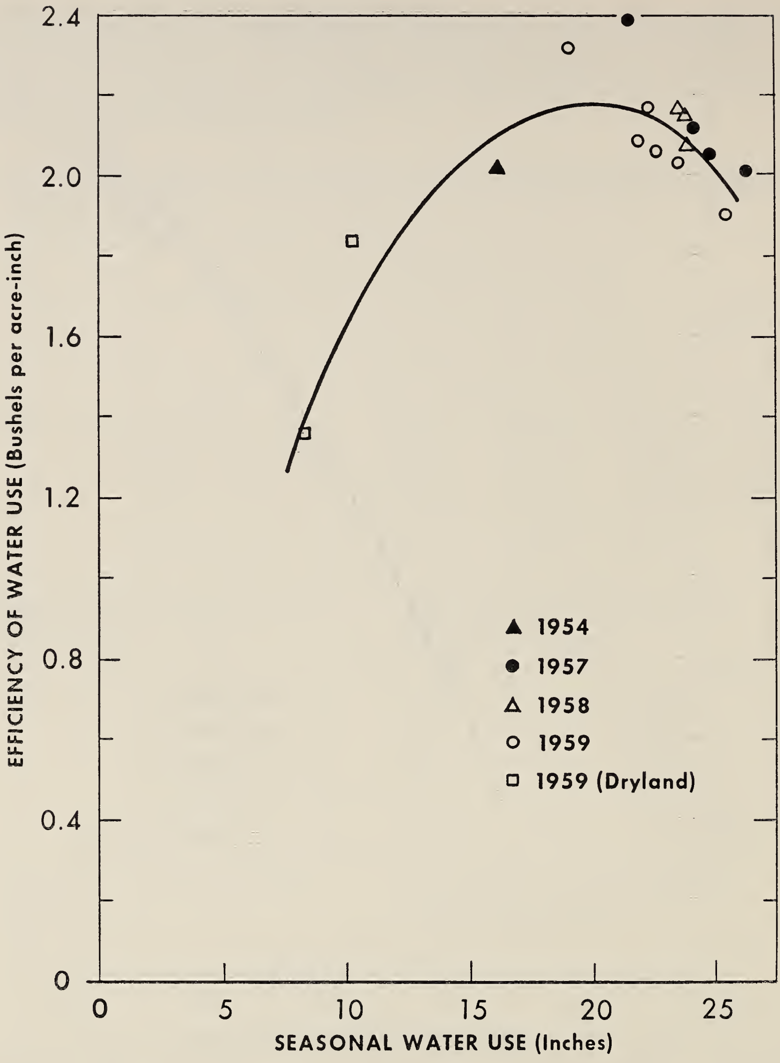

FIGURE 3.—Relation between seasonal water use and efficiency of water use for grain production, 1954 and 1957 to 1959.

minimum efficiency of water use measured under high moisture availability was 1.90 bushels per acre-inch.

Applied nitrogen had little effect on the total seasonal water use in 1959. No visual effect on vegetative growth was apparent until about boot stage. Where nitrogen increases grain yields considerably, an increase in water-use efficiency can be expected.

TABLE 10.—*Variability of water use, grain yield, and efficiency of water use for the "dry" irrigation treatment in relation to type of season (precipitation), 1954–59*

Type of season (precipitation)	Seasonal water use	Grain yield	Efficiency of water use
	Inches	*Bu./acre*	*Bu./acre-inch*
Dry—1954	16. 21	32. 8	2. 02
Below normal—1959	19. 06	44. 1	2. 32
Above normal—1957	21. 46	51. 2	2. 39
Wet—1958	23. 51	50. 9	2. 17

Grain Quality

The effects of water management and applied nitrogen on grain, flour, and breadbaking quality data for 1954 and 1957 to 1959 are presented in tables 11 through 14. Both Comanche grown in 1954 and 1955 and Bison in 1957 to 1959 possess very good quality characteristics (*2*, *6*). No quality tests other than test weights were made on the 1955 yields.

The most important quality characteristic is protein. Miller and Johnson (*13*) have reported that, "The amount of protein is the simplest and best single indicator of flour quality. The quantity of protein in wheat that is grown under favorable environmental conditions accounts for the major quality differences. However, when wheat is grown under abnormal environmental conditions, the quality of the protein accounts for most of these differences."

Maintenance of higher available soil moisture with additional irrigations decreased protein quantity of grain, whereas higher nitrogen rates increased protein quantity. These relationships are illustrated in figure 4. Data from the 1958 test are not included in figure 4, owing to lack of response to irrigation as a result of unusually high rainfall and to the small carryover effects from residual nitrogen. For applied nitrogen rates up to 60 pounds per acre, increasing the soil moisture level from "dry" to "med" decreased grain protein only slightly from an average value of 12.94 to 12.86 percent. When soil moisture was maintained at a higher level with the "wet" treatment, average protein quantity decreased considerably to 12.11 percent. Protein quantity of dryland fallow yields was considerably higher for the 2 years in which limited data are available (tables 13 and 14).

The higher soil moisture levels improved protein quality as reflected in higher loaf volumes when adjusted to a constant protein quantity. Increasing the soil moisture level from "dry" to "med" increased the average adjusted loaf volume from 949 to 967 cc. for the response years of 1954, 1957, and 1959. An additional increase in soil moisture level to "wet" further increased the average adjusted loaf volume to 992 cc. These data indicate that the improved quality somewhat compensated for the decreased protein quantity from higher moisture treatments. Therefore, increasing soil moisture to the "med" treatment, which produced near maximum yields, may not detrimentally affect breadbaking quality.

TABLE 11.—*Effect of water management and applied nitrogen on milling and baking quality of irrigated Comanche winter wheat, Garden City, Kans., 1954* [1]

Nitrogen treatment (lb./acre)	Wheat			Flour		Breadbaking data				
									Loaf volume	
	Ash	Protein	Flour yield	Ash	Protein	Absorption	Mixing time	$KBrO_3$ requirement	As received	Corrected to 13.0 percent protein
"DRY" IRRIGATION (FALL ONLY)										
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Min.*	*Mg.*	*Cc.*	*Cc.*
Check	1. 84	12. 4	70. 2	0. 54	12. 0	64. 2	3. 5	2	864	936
50	1. 86	13. 0	70. 1	. 54	12. 4	64. 4	3. 6	2	872	912
100	1. 96	14. 4	69. 6	. 58	13. 5	65. 4	3. 5	2	961	928
200	1. 96	15. 3	69. 2	. 54	14. 7	66. 3	3. 5	3	1, 033	921
Average	1. 90	13. 8	69. 8	. 55	13. 2	65. 1	3. 5	2	932	924
"MED" IRRIGATION (FALL+BOOT)										
Check	1. 82	12. 2	75. 4	0. 59	11. 7	64. 4	3. 2	3	862	956
50	1. 88	13. 0	75. 4	. 62	12 4	64. 8	3. 0	3	924	967
100	2. 10	13. 6	75. 5	. 62	13. 2	65. 4	3. 2	3	955	944
200	1. 94	14. 6	74. 9	. 62	14. 2	67. 0	3. 0	3–4	1, 025	940
Average	1. 94	13. 4	75. 3	. 61	12. 9	65. 4	3. 1	3	942	952

"WET" IRRIGATION (FALL + WINTER + JOINT + FLOWERING + DOUGH)

Check	1. 79	11. 1	75. 6	0. 54	10. 6	61. 2	3. 2	1	824	1, 004
50	1. 80	11. 8	75. 8	. 54	11. 0	62. 6	3. 0	2	856	1, 007
100	1. 80	12. 8	75. 6	. 54	12 0	63. 3	3. 0	2	899	966
200	1. 78	13. 8	74. 2	. 52	13. 2	63. 5	2. 9	2–3	988	978
Average	1. 79	12. 4	75. 3	. 54	11. 7	62. 6	3. 0	2	892	989

[1] Chemical data expressed on a 14-percent moisture basis.
Crumb grains and colors were satisfactory for all treatments.

TABLE 12.—*Effect of water management and applied nitrogen on milling and baking quality of irrigated Bison winter wheat, Garden City, Kans., 1957* [1]

Nitrogen treatment (lb./acre)	Wheat			Flour		Breadbaking data				
									Loaf volume	
	Ash	Protein	Flour yield	Ash	Protein	Absorption	Mixing time	$KBrO_3$ requirement	As received	Corrected to 12.0 percent protein
"DRY" IRRIGATION (FALL ONLY)										
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Min.*	*Mg.*	*Cc.*	*Cc.*
Check	1.50	12.0	76.7	0.38	11.2	60.4	4.2	1–2	900	956
30	1.48	12.9	77.0	.42	12.1	61.7	3.9	2–3	952	944
60	1.48	13.1	76.4	.40	12.4	61.6	4.0	2	968	942
120	1.48	13.4	77.1	.42	12.6	61.8	3.8	2–3	1,006	956
Average	1.48	12.8	76.8	.40	12.1	61.4	4.0	2	956	950
"MED" IRRIGATION (FALL+BOOT)										
Check	1.64	12.4	76.6	0.40	11.7	61.2	4.0	2	936	958
30	1.60	12.6	76.8	.43	12.1	61.2	3.6	2–3	960	953
60	1.59	13.3	75.8	.40	12.7	61.2	3.6	2–3	1,014	961
120	1.62	13.6	76.6	.41	13.2	61.8	3.5	3	1,044	958
Average	1.62	13.0	76.4	.41	12.4	61.4	3.7	2–3	988	958

"WET" IRRIGATION (FALL + WINTER + BOOT + MILK)

Check	1.60	11.1	77.4	0.44	10.9	60.6	3.6	1–2	894	976
30	1.60	11.8	76.8	.40	11.3	60.6	3.5	2	932	984
60	1.58	12.4	76.5	.40	11.8	61.0	3.4	2	946	962
120	1.58	12.6	77.4	.44	12.2	61.6	3.4	2	970	959
Average	1.59	12.0	77.0	.42	11.6	61.0	3.5	2	936	970

[1] Chemical data expressed on a 14-percent moisture basis.
Crumb grains and colors were satisfactory for all treatments.

TABLE 13.—*Effect of water management and residual nitrogen on milling and baking quality of irrigated Bison winter wheat, Garden City, Kans., 1958. Quality of Bison wheat grown on dryland fallow is included for comparison* [1]

Nitrogen treatment residual (lb./acre)	Wheat			Flour		Breadbaking data				
									Loaf volume	
	Ash	Protein	Flour yield	Ash	Protein	Absorption	Mixing time	$KBrO_3$ requirement	As received	Corrected to 11 percent protein
DRYLAND FALLOW										
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Min.*	*Mg.*	*Cc.*	*Cc.*
None	1. 89	16. 7	74. 2	0. 41	14. 7	62. 9	3. 6	2	1, 106	[2] 1, 091
"DRY" IRRIGATION (FALL ONLY)										
Check	1. 69	11. 3	78. 6	0. 44	10. 4	62. 9	4. 0	1–2	873	913
60	1. 65	11. 5	77. 8	. 42	11. 0	61. 5	4. 0	2	910	910
120	1. 60	12. 4	78. 4	. 42	11. 6	63. 3	3. 5	3	950	905
Average	1. 65	11. 7	78. 3	. 43	11. 0	62. 6	3. 8	2	911	911

"MED" IRRIGATION (FALL+MILK)										
Check	1. 71	11. 0	78. 5	0. 45	10. 2	62. 9	4. 4	1–2	880	940
60	1. 68	11. 8	77. 1	. 42	11. 0	61. 3	3. 8	2–3	916	916
120	1. 52	12. 2	79. 0	. 45	11. 6	63. 0	3. 2	3	945	900
Average	1. 64	11. 7	78. 2	. 44	10. 9	62. 4	3. 8	2–3	914	919
"WET" IRRIGATION (FALL+BOOT+HEADING+MILK)										
Check	1. 72	11. 8	76. 5	0. 43	11. 3	63. 9	3. 9	2	930	907
60	1. 71	12. 1	78. 1	. 42	11. 4	62. 9	4. 0	2–3	933	903
120	1. 59	12. 3	78. 1	. 44	11. 8	63. 5	3. 5	3	953	893
Average	1. 67	12. 1	77. 6	. 43	11. 5	63. 4	3. 8	2–3	939	901

[1] Chemical data expressed on 14-percent moisture basis.
Crumb grains and colors were satisfactory for all treatments.
[2] Corrected to 14.5 percent protein.

TABLE 14.—*Effect of water management and applied nitrogen on milling and baking quality of irrigated Bison winter wheat, Garden City, Kans., 1959* [1]

Nitrogen treatment residual (lb./acre)	Wheat			Flour		Breadbaking data				
									Loaf volume	
	Ash	Protein	Flour yield	Ash	Protein	Absorption	Mixing time	$KBrO_3$ requirement	As received	Corrected to 12.5 percent protein
DRYLAND FALLOW										
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Min.*	*Mg.*	*Cc.*	*Cc.*
None	1.70	15.6	71.2	0.44	14.5	64.5	5.4	2–3	1,150	[2] 1,150
"DRY" IRRIGATION (FALL ONLY)										
Check	1.44	12.9	78.0	0.41	12.4	60.9	4.2	1–2	967	975
60	1.43	14.0	77.4	.42	13.4	60.5	4.9	2	1,030	963
120	1.46	14.1	75.1	.41	13.3	58.7	4.0	1–2	1,037	977
Average	1.44	13.7	76.8	.41	13.0	60.0	4.4	1–2	1,011	972

"MED" IRRIGATION (FALL+BOOT)

Check	1. 53	12. 6	76. 1	0. 40	12. 0	58. 5	4. 2	1	955	993
60	1. 46	13. 8	75. 1	. 39	12. 7	59. 2	4. 0	1–2	1, 018	1, 003
120	1. 50	13. 8	75. 5	. 40	13. 0	59. 5	4. 1	1–2	1, 022	984
Average	1. 50	13. 4	75. 6	. 40	12. 6	59. 1	4. 1	1–2	998	993

"WET" IRRIGATION (FALL+JOINT+BOOT+FLOWERING+MILK)

Check	1. 66	12. 7	75. 6	0. 42	11. 8	58. 5	4. 1	1–2	950	1, 003
60	1. 62	13. 5	75. 4	. 43	12. 5	58. 8	3. 8	2	1, 010	1, 010
120	1. 58	13. 4	74. 5	. 43	12. 6	58. 3	4. 0	2	1, 045	1, 037
Average	1. 62	13. 2	75. 2	. 43	12. 3	58. 5	4. 0	2	1, 002	1, 017

[1] Chemical data expressed on 14-percent moisture basis.
Crumb grains and colors were satisfactory for all treatments.
[2] Corrected to 14.5-percent protein.

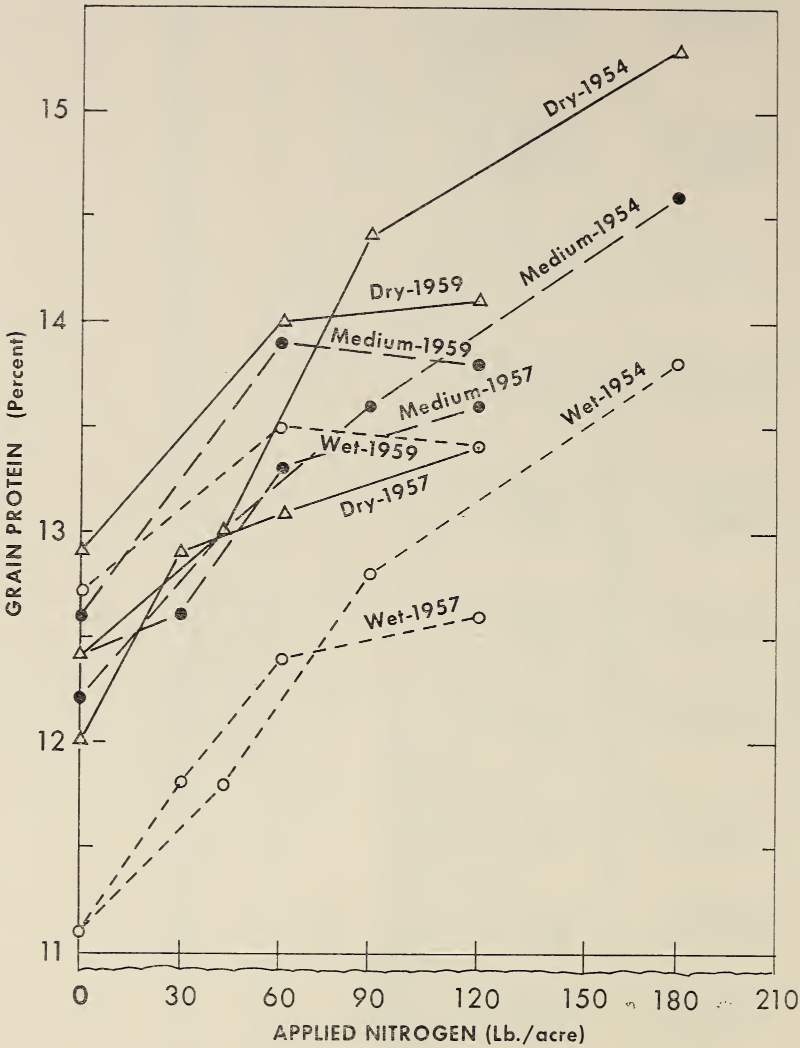

FIGURE 4.—Relation between applied nitrogen (N) and grain protein percentage for "dry," "medium," and "wet" irrigation treatments.

Applied nitrogen consistently increased protein quantity under all conditions (fig. 4). For rates up to 60 pounds per acre, protein quantity increased from 0.013 to 0.022 percent per pound of applied nitrogen. The average increase was 0.018 percent per pound. Higher rates of applied nitrogen had a much smaller effect on protein quantity in 2 of 3 years, indicating that the nitrogen-protein relationship may be curvilinear. The shape of the nitrogen-protein curves was similar for the different irrigation treatments.

If the effects of soil moisture and nitrogen availability are considered, proper management of irrigation water and nitrogen fertility should permit high production of grain with acceptable baking quality characteristics. Varieties having excellent quality characteristics must be used, however. Proper management will also minimize the variability in grain quality associated with effects of widely varying soil and weather conditions within a general climatic area.

Test weights are not an important characteristic of flour and bread-baking quality; however, low test weights or shriveled grain will decrease flour yields. Effects of water management and applied nitrogen on test weights are presented in table 15. Test weights from dryland fallow yields are included for comparison.

Adequate irrigation for near maximum yields produced the highest test weights. High soil moisture levels that required excessive irrigation slightly decreased test weights in some years. Moisture stress that caused grain shriveling in 1954 decreased test weights from 59.4 pounds per bushel on the "wet" treatment to 52.8 on the "dry" treatment. The lower test weights decreased flour yields from 75.3 to 69.8 percent. In all years irrigated wheat has produced significantly higher test weights than the same variety grown on dryland fallow.

Higher rates of applied nitrogen consistently decreased test weights slightly. This decrease, which ranged from less than 1.0 to 7.7 percent, was greater during the drier seasons. Under severe moisture stress in 1954, the 200 pounds per acre nitrogen treatment decreased test weights from 54.6 to 50.4 pounds per bushel. This decrease may have resulted from a nitrogen response, which accelerated moisture use and increased severity of moisture stress.

Plant Lodging

Soil moisture and nitrogen treatments were associated with severity of plant lodging from spring storms in May and early June 1957. Treatment effects, measured at representative sites in all plots at harvest, are illustrated in figure 5. Each point plotted is an average of 10 subplots. Very little lodging occurred with the "dry" treatment. Lodging on the "med" treatment plots decreased plant height consistently from 42 inches on check plots to 27 inches on the high nitrogen plots. On the "wet" treatment plots, plant height was decreased rapidly from 44 inches on check plots to a lodged height of 23 inches on plots receiving 60 pounds per acre applied nitrogen. Additional nitrogen had only a slight effect. Applied nitrogen did not affect plant height before lodging. Increased lodging was observed also after storms in 1954 and 1955 on the high-moisture and high-nitrogen plots.

Within a given variety, susceptibility of lodging is associated with rank straw growth, which contributes to increased height and weight and decreased straw strength. An additional effect of high soil moisture may be decreased root anchorage and plant ability to upright after severe storms. Excessive irrigation and nitrogen fertilization should be avoided to minimize potential lodging.

TABLE 15.—*Test weights for water management and applied and residual nitrogen treatments for different climatic years compared with dryland fallow, Garden City, Kans., 1954, 1955, and 1957 through 1959*

Year	Precipitation, Mar. 1–June 15 [1]	Dryland fallow [2]	Nitrogen rate	Irrigation treatments			
				"Dry"	"Med"	"Wet"	Average
	Inches	*Lb./bu.*	*Lb./acre*	*Lb./bu.*	*Lb./bu.*	*Lb./bu.*	*Lb./bu.*
1954	2.67 (dry)	49.0	Check	54.6	58.2	60.2	57.7
			50	54.0	56.4	60.0	56.8
			100	52.2	54.6	58.7	55.2
			200	50.4	54.4	58.6	54.5
			Average	52.8	55.9	59.4	56.0
1955	8.20 (above normal).	60.1	Check [3]	60.4	59.8	59.0	59.7
			50	60.0	60.0	59.0	59.7
			100	60.1	59.8	58.8	59.6
			200	59.2	59.7	58.9	59.3
			Average	59.9	59.8	58.9	59.6
1957	8.90 (above normal).	44.9	Check	60.2	59.5	60.8	60.2
			30	60.5	60.1	60.4	60.3
			60	59.9	59.1	59.7	59.6
			90	59.6	57.9	59.0	58.8
			120	60.0	57.8	59.0	58.9
			Average	60.0	58.9	59.8	59.6
1958	11.78 (wet)	56.3	Check [3]	62.0	61.7	61.6	61.8
			30	61.5	61.7	61.9	61.7
			60	61.4	61.5	61.7	61.5
			90	61.7	61.2	61.6	61.5
			120	61.1	60.9	61.3	61.1
			Average	61.5	61.4	61.6	61.5
1959	4.94 (below normal).	55.0	Check	59.4	59.5	59.6	59.5
			30	59.2	58.9	59.1	59.1
			60	58.9	59.1	58.1	58.7
			90	58.4	58.7	58.6	58.6
			120	58.6	58.4	57.7	58.2
			Average	58.9	59.0	58.6	58.8
Average (all years)		53.1	----------	58.6	59.0	59.7	59.1

[1] 50-year average precipitation, Mar. 1–June 15=6.95 inches.
[2] Test weights on dryland fallow yields were taken from variety tests, Garden City Experiment Station. Dryland fallow yield in 1957 was limited by delayed emergence (spring).
[3] Carryover from nitrogen application the previous year.

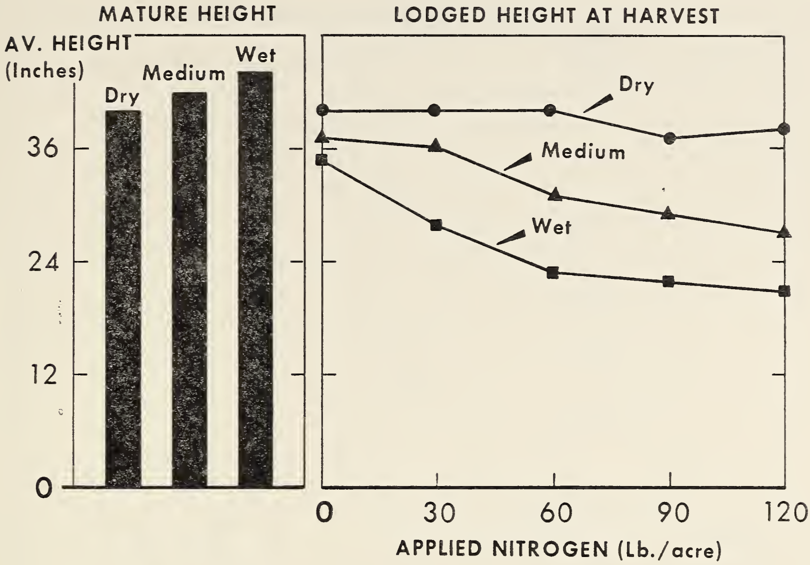

FIGURE 5.—Effects of water management and applied nitrogen on the lodged height at harvest, 1957.

Moisture Extraction Patterns, Timing, and Depth of Irrigations

Extraction Patterns

Moisture extraction patterns illustrate relative amounts of water that plants use from successive increments of soil depth. During fall growth, wheat plants use moisture largely from the top foot of soil. In the fall of 1958, 40 to 50 percent of the water used came from the top foot. During early-spring growth, water used from the top foot decreased proportionately to approximately 30 percent. A moisture extraction pattern during the early-spring growth in 1959 is illustrated in figure 6. The rate of extraction decreased successively from 29.7 percent from the top foot to 7.2 percent from the sixth foot, pattern A. Roots were observed to a depth of 6 feet in soil samples during early-spring growth.

Moisture extraction patterns are related to root density and also to moisture availability. Water was more readily available in the top 4 feet after irrigation but less available in this depth when irrigation was delayed. This effect is illustrated in figure 6. After irrigation to 4 feet, extraction from the fifth and the sixth foot decreased 7.6 and 2.6 percent, respectively, pattern B. When irrigation was delayed, extraction from the fifth and the sixth foot increased to 25.1 and 21.2 percent, respectively, pattern C.

The major depth for moisture extraction was 0 to 4 feet. Moisture is not rapidly used from the fifth and sixth feet until it becomes less available in the top 4 feet. Some depletion may have occurred below the 6-foot depth on the drier treatments.

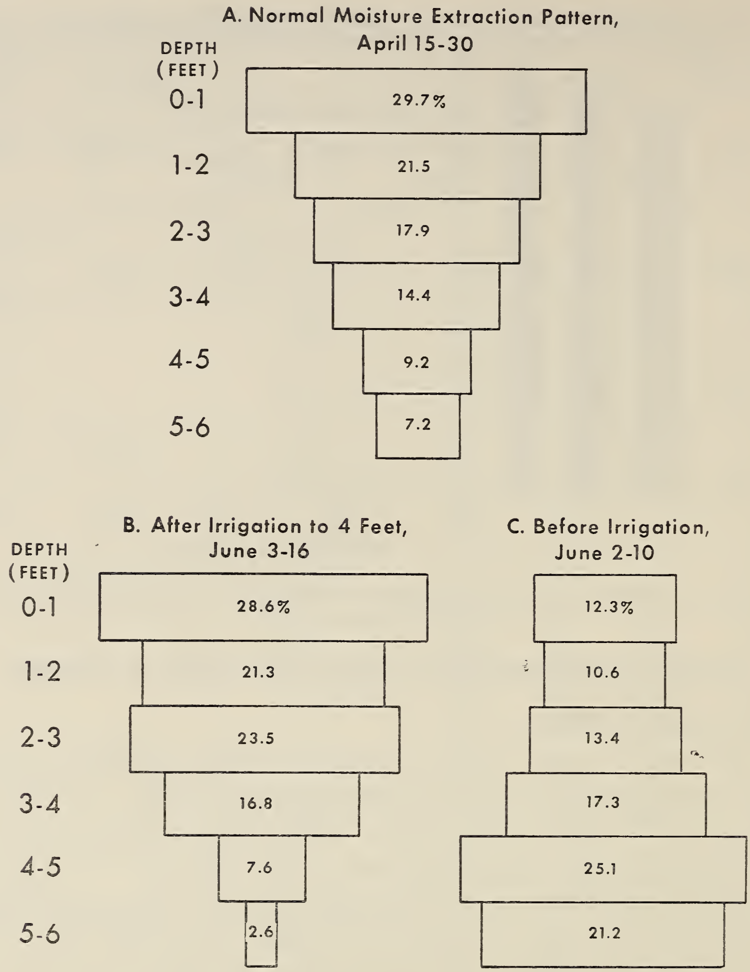

FIGURE 6.—Moisture extraction patterns under different conditions of soil moisture availability with depth during periods of no rainfall, 1959.

Soil moisture depletion curves for the "dry" treatment during the spring growing season, 1959, are presented in figure 7. Curves are presented for each foot of depth to 6 feet with exception of the first foot. This depth was excluded because of periodic accumulation of moisture from rainfall. The curves illustrate moisture availability and depletion characteristics with depth throughout the spring growing season.

Timing of Irrigations

Optimum yields have resulted from fall irrigation only ("dry" treatment) in years of above normal precipitation for the rest of the crop

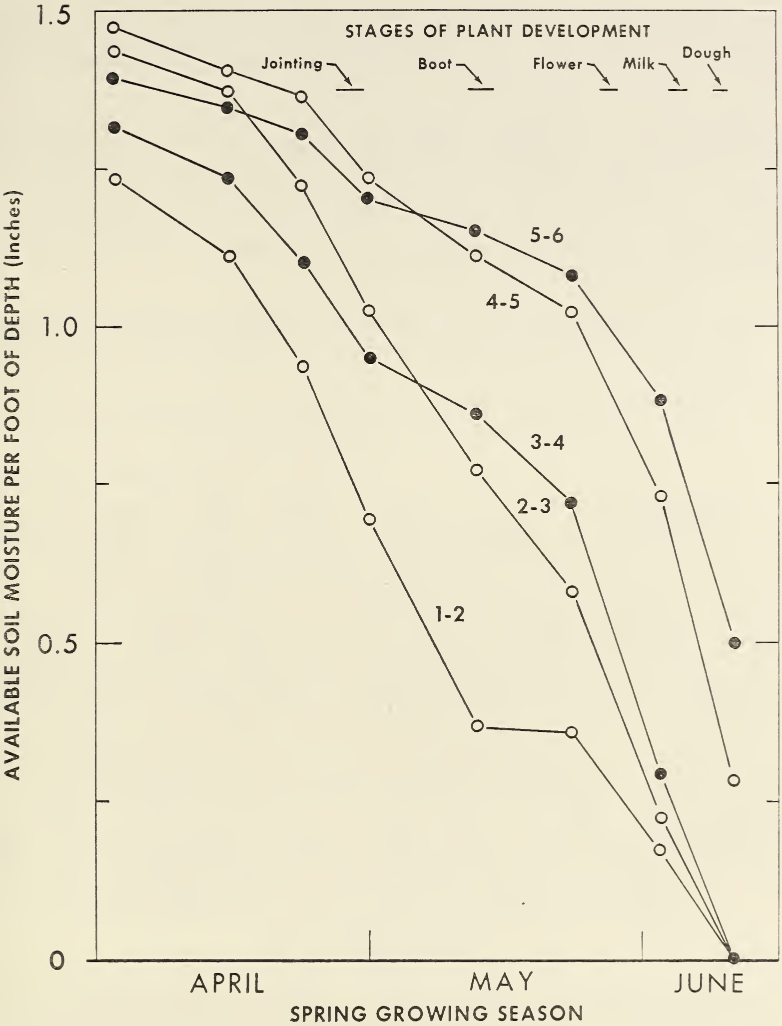

FIGURE 7.—Soil moisture depletion curves for 2d through 6th foot of depth, "dry moisture treatment, 1959. The 1st foot is excluded because of periodic accumulation of moisture from rainfall.

year, and from an additional irrigation at boot stage ("med" treatment) in years when precipitation was below normal. Since precipitation cannot be predicted, a spring irrigation should be considered for the boot-through-heading stages of growth.

Fall irrigation more than doubled the average dryland yields (21 bu.) for the 5-year period. A winter irrigation when added to selected treatments did not affect yields significantly in the 3 years tested (table 16). If a preplanting irrigation was not applied or did not wet

the soil at least to 4 feet on fine-textured soils, a late-fall or winter irrigation is desirable. If wheat was planted early for pasture, a late-fall or winter irrigation may be desirable to replenish the extra water used during early-fall growth.

An irrigation during early-spring growth usually is not required. Delaying this irrigation to boot stage will minimize excessive straw growth from high soil moisture during spring tillering-through-jointing stages. Fruiting occurs during the peak water-use period and is the most critical stage for moisture stress. On fine-textured soils, an irrigation at boot stage to 4 or 5 feet will store adequate water for plant use through grain development.

TABLE 16.—*Grain yields from irrigating to 2 depths at different stages of plant growth in Richfield clay loam, Garden City, Kans., 1954, 1955, and 1957*

Year and depth of wetting, each irrigation	Irrigation treatment					
	Fall ("dry")	Fall plus winter	Fall plus boot stage ("med")	Fall plus winter plus boot stage	"Wet" treatment	Average
1954						
Depth:	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*
3½ feet	34. 9	32. 8	43. 1	38. 1	47. 5	39. 3
7 feet	30. 8	32. 9	48. 2	41. 9	48. 2	40. 4
Average	32. 8	32. 8	45. 6	40. 0	47. 8	39. 8
1955						
Depth:						
2 feet	42. 8	45. 3	49. 9	54. 5	47. 0	47. 9
6 feet	49. 9	54. 7	47. 8	47. 5	45. 8	49. 1
Average	46. 2	50. 0	48. 8	51. 0	46. 4	48. 5
1957						
Depth:						
2 feet	48. 8	52. 0	49. 7	52. 7	53. 0	51. 2
6 feet	53. 5	50. 8	52. 5	53. 3	52. 5	52. 5
Average	51. 2	51. 4	51. 1	53. 0	52. 7	51. 9

To use a limited water supply most efficiently for a large acreage, one fall irrigation can be applied in September through November when the irrigation water is not being used on other crops. A spring irrigation may be applied during a 4-week period in May or during the jointing-through-flowering stages of development. Table 17 gives the acreage that can be irrigated for each 100-gallon-per-minute water supply for different amounts of water storage required. Calculations were based on applying water an average of 22 hours per day for an average irrigation efficiency of 65 percent. Irrigation efficiency is defined as the percentage of water pumped or delivered to the farm

TABLE 17.—*Maximum acreage irrigable per 100 g.p.m. (gallons per minute) water supply for one spring irrigation in May, jointing through flowering stages of development (4 weeks)*

Storage required in soil (inches)	Pumping required for 65 percent irrigation efficiency	Acreage irrigated per 100 g.p.m. pumped[1]
	Acre-inches	*Acres*
4. 0	6. 2	20
6. 0	9. 2	15
8. 0	12. 3	10

[1] Assuming water is applied an average of 22 hours per day.

that is stored in the soil for plant use. Irrigation of wheat in May does not greatly interfere with irrigation schedules for other cropland.

Depth of Irrigations

In the Garden City tests, irrigation treatments included water application for two depths of wetting in 3 years. Water was applied to wet the soil to 3½ and 7 feet in 1954 and to 2 and 6 feet in 1955 and 1957. The effects of depths of wetting on grain yields are presented in table 16. The increase in yields from the deeper irrigation tested statistically significant on only one treatment, preplanting plus winter irrigations in 1955. The lack of response to the deeper irrigations resulted from moisture being available below the shallow depth of wetting from the previous year and from above-normal precipitation in 2 of the 3 years.

These results indicate that when wheat is irrigated in fall to about 6 feet, spring irrigations need not wet the soil to the same depth. In the 1958 and 1959 experiments, spring irrigations were applied to wet the soil to 4 feet, which required storage of 3.5 to 7.0 inches of water in the soil. Water storage from an irrigation at boot stage was adequate to mature the crop without incurring moisture stress.

CONCLUSIONS

1. Fall irrigation to 6 feet in 4 years with approaching normal to above-normal precipitation produced near maximum grain yields of 44 to 51 bushels per acre. One additional irrigation at boot stage in the dry spring of 1954 increased yields 12.9 bushels per acre. Additional irrigations did not affect yields significantly.
2. Applied nitrogen increased grain yields up to 6 bushels per acre for rates of 30 to 60 pounds per acre. High rates decreased yields and test weights. Residual nitrogen on the higher treatments increased yields significantly in 1 of 2 years.
3. Optimum seasonal water use was 22 to 24 inches; maximum use, 24 to 26 inches; and most efficient use for grain production, 20 to 22 inches. The peak rate of use was 0.35 inch per day, which occurred from flowering-to-milk stage of grain. Fruiting stage of development was most critical for moisture stress.

4. Efficiency of water use decreased under severe moisture stress, excessive irrigation, and low nitrogen availability. Maximum efficiency of water use was about 2.4 bushels per acre-inch.

5. Considerable moisture stress did not occur until soil moisture closely approached the permanent wilting percentage. Wheat entered the spring growing season with an extensive rooting system. This rooting system, which exceeded 6 feet in depth, was able to explore thoroughly the soil for moisture extraction.

6. High moisture and nitrogen availability during spring tillering-through-jointing stages caused rank straw growth. The desirable low straw/grain ratios (pounds of straw produced per pound of grain) occurred on the lower irrigation and nitrogen treatments.

7. Higher soil moisture and nitrogen availability decreased resistance to lodging. Lodging was slight on the optimum irrigation and nitrogen treatments as compared to severe lodging in some years under excessive irrigation and high nitrogen fertilization.

8. Irrigated wheat consistently produced high test weights. In 1954, spring irrigations were required to prevent shriveling from hot, drying winds.

9. Grain protein quantity decreased with increasing soil moisture availability, but protein increased with increased nitrogen availability. Increasing moisture availability increased protein quality, loaf volume per increment of protein, which somewhat compensated for decreased quantity. Grain with satisfactory quality was produced when excessive irrigation was avoided. Nitrogen increased protein quantity from 0.013 to 0.022 percent per pound of applied N for rates up to 60 pounds per acre.

10. Monthly coefficients for the Blaney-Criddle consumptive-use formula were 0.57 in October, 0.32 to 0.36 in late fall and winter dormancy, 0.40 in March, 0.81 in April, 1.08 in May, and 1.00 in June. Seasonal coefficient was 0.71.

11. Efficient use of a limited water supply may be realized by spreading the water over a large acreage. Fall irrigation during September through November will provide beneficial use of available water when it is not needed for irrigating other crops.

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